Unbalanced Quenching in a Long Solenoid with Separately Powered Coils

M. A. Green[1], H. Pan[1], S. O. Prestemon[1], B Strauss[2], and V. Kashikhin[3]

***Abstract*—Quenches were simulated for a long solenoid composed of five separately powered coils. Two coils, at one end of the magnet, are separately powered by 300-A power supplies, so that the uniform field section of the magnet is matched to the rest of a physics experiment. The three coils in the uniform field end are connected in series and are powered by a single 300-A power supply. The two end coils of the three-coil set use separate 60-A power supplies to trim the uniform field. Quench back from the 6061-Al mandrel is an important part of the quench protection for the three-coil section. Quench propagation from one separately powered coil to the next was simulated by using the Opera3D program of the Vector Fields. Low current quench simulations showed that some coils carry currents for a long time before quenching. Since the magnet doesn't quench all at once, there can be unbalanced forces developed in the coils and the thermal shield.**

***Index Terms*—Superconducting Magnet, OPERA-3D, Quench, Eddy current**

I. Introduction

Two superconducting solenoids were designed to produce a uniform solenoidal magnetic field ($\Delta B/B < 0.003$) within 0.4-m diameter warm bore. The good field region is 1.0-m long and 0.3-m in diameter [1]. Fig. 1 shows the physical structure of this long solenoid. The uniform field region is occupied by five planes of scintillating fiber detector that measure the position in 3D space of π^+, π^-, μ^+, μ^-, e^+ and e^- as they spiral around in the solenoid field. A uniform field from 2.8 to 4.0 T (both polarities) is generated by a triplet coil set consisting of a single 1.3-m long center solenoid and two 0.06-m long end coils that shape the field [2]. The uniform field section is matched to the rest of the experiment by two coils M1 and M2 that that can produce a maximum induction of 2.5 T (both polarities) on axis. The relevant physical parameters of the five coils are given in Table I [3], [4]. The magnet and its shields are cooled by five two-stage 4.2 K coolers [5], [6]. The electrical diagram for the magnet is shown in Fig. 2. Cold diodes and a resistor are across each coil [7]. The triplet coil set and the two match-coils are powered by three single-polarity 300-A power supplies. There is a dump circuit across each of the powered sections.

Manuscript received July 17, 2013. This work is supported by the Office of Science, US-DOE under DOE contract DE-AC02-05CH11231.

M. A. Green, H. Pan, and S. Prestemon, are with Lawrence Berkeley Laboratory, Berkeley, CA, 94720 (email: magreen@lbl.gov, 510-333-1553; hengpan@lbl.gov; soprestemon@lbl.gov).

B. Strauss is with the Office of Science, US Department of Energy, Germantown MD (email: bruce.strauss@science.doe.gov.

V. Kashikhin is with Fermi National Accelerator Laboratory, Batavia, IL 60510, USA, (e-mail: kash@fnal.gov).

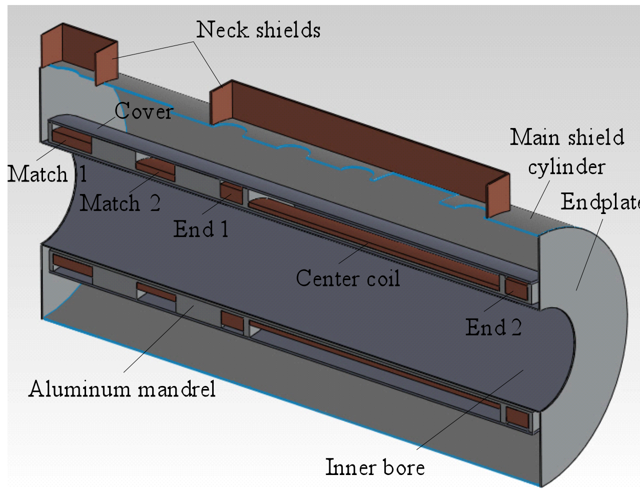

Fig. 1: Cold mass cross section of the long five-coil solenoid magnet

TABLE I. Parameters of Each Coil

Parameter	M1	M2	E1	C	E2
Number of turns/layer	120	119	66	784	62
Number of layers	42	28	56	20	66
Inner radius (mm)	258	258	258	258	258
Outer radius (mm)	303	288	318	279	324
Axial coil length (mm)	201	199	111	1314	111
Self-Inductance (H)	12.0	5.0	9.0*	39.9*	11.3*

* The self-inductance of coils E1, C, and E2 hooked in series is 74 H.

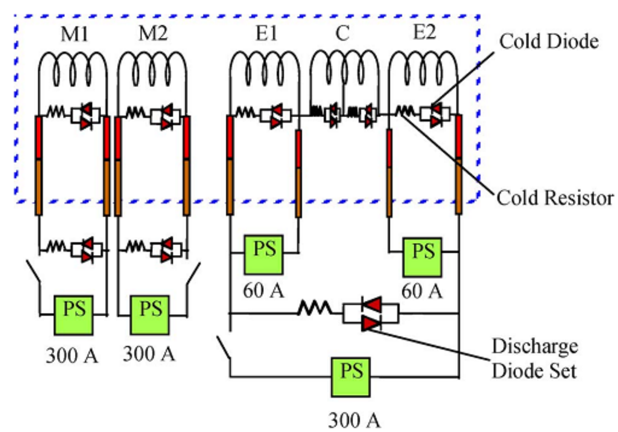

Fig. 2: Electrical connections of the five-coil solenoid magnet

At a current of 275 A, the five individual coils have a stored energy in the range from 0.19 MJ to 1.51 MJ. The 1.3-m long center coil (C) for the uniform field section has the largest stored energy. When coils E1, C, and E2 are connected in series, the total stored energy at 275 A is 2.8 MJ. The two end coils and the center coil are protected using four sets of back-to-back diodes and 0.02-ohm resistors. The center coil C is sub-divided radially into two sub-sections C1 and C2. Each section of the center coil has diodes and a resistor across it.

Since the coils are distributed longitudinally, the quench propagation spreads sequentially from one coil to the next by thermal diffusion with quench-back. Unlike the quenches in the short coils, a quench in the long solenoid C is greatly speeded up by quench-back from the 6061-Al mandrel [8]. A quench in one coil will quench the whole magnet [9].

The magnet cold mass is 2.544 m long with a cold bore of 0.49 m. With the coils spaced along the length and a high stored energy, the quenches in the coils do not happen all at once. As a result, the quench propagation from one end of the magnet to the other end is an important design consideration. This paper describes the quench propagations and effects of an unbalanced quench. The results reported were calculated using the Opera3D finite element quench program.

II. Quench Simulations

A. Computation model

A 3D finite element quench model considering both the subdivision and quench-back was created in the Opera3D program. The model is capable of combining the 3D transient magnetic field calculation (ELEKTRA) into the 3D thermal calculation (TEMPO). The transient magnetic field was updated by ELEKTRA at each time step and shifted to the thermal model, in which the Joule heat generation and transient temperature distribution were evaluated. Eddy currents in the bobbin were solved for each time step. This enabled the computation of the quench-back effect in the model.

A diode forward voltage of 4.5 K of 8 V was initially assumed in the model. Once the quench protection circuit conducts, the forward voltage was set to drop to 1.6 V, because of diode heating. The voltage across the coil that originated quench was used to disconnect the power supplies.

B. Quench starts from the center coil at 265 A

Coil C is the longest coil in the magnet. It is possible that a quench can start in this coil. In Fig. 3, a heat was applied in the inside center of the inner layer of the inner section C1.

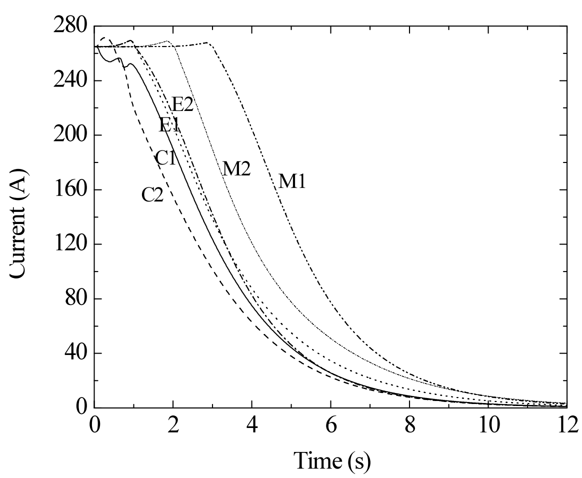

Fig. 3: Current decay after the quench started in the center of C1 at 265 A

Currents in all coils shown in Fig. 3 dropped to zero in 10 s. The M1 coil, which is the furthest one from the center coil, started to quench 3 s after the quench started in the center coil. Because the center coil is long, quench–back plays a dominant role in the center coil quench propagation [8].

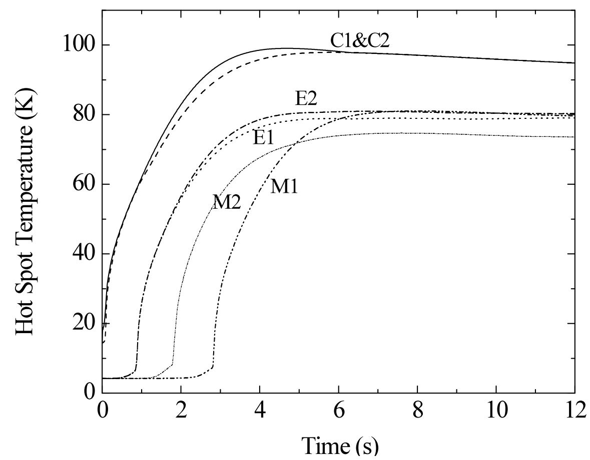

Fig. 4: The adiabatic hot spot temperature after the quench started in the center of coil C1 at 265 A

The hot spot temperature of all coils shown in Fig. 4 for the Fig. 3 case. The maximum hot spot temperature is ~100 K. The center coil took ~1.5 s to become fully normal because of quench back. The maximum mandrel temperature is ~70 K.

C. Quench starts from E2 coil at 265 A

The highest field in the magnet is located in coil E2 coil on the end of the magnet assembly. At high operating currents, this coil produces the largest lateral force compared to the other coils. Quenches are most likely to occur in the E2 coil.

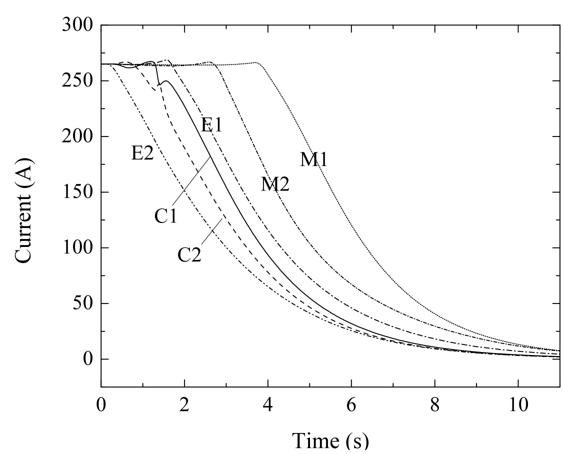

Fig. 5: Current decay after the quench started in E2 at 265 A

As part of the triplet coil set, the E2 coil strongly couples with the center coil and the E1 coil. The magnet quench took ~3.8 s to get to the M1 coil at the other end of the magnet (see Fig 5). The current decay time constant is ~ 4 s.

The maximum hot spot temperature of 116 K is in both center coils due its large stored energy and its longer propagation time compared to the other coils even with quench back (see Fig. 6). In this case, the quench propagated along the center coil longer before quench back took over.

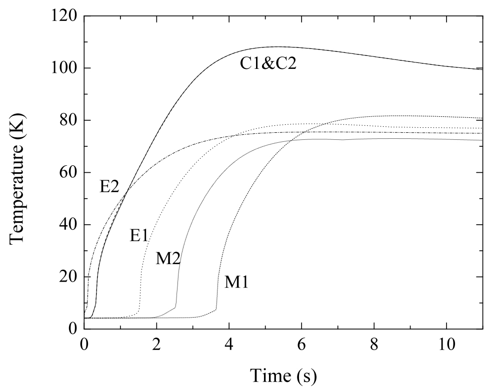

Fig. 6: Hot spot temperature after the quench started in E2 at 265 A

Fig. 7 shows the quench propagation through the entire solenoid from the E2 end to the M1 of the magnet. The quenches in the entire solenoid do not happen all at once. Heat generated in the E2 coil spreads to the center coil by heat diffusion. Once the center coil starts to quench, quench back occurs relatively quickly (in ~1.0 s) [9]. Without quench back, the quench propagation in the long solenoid would be ~7 s. The G10 spacers between coils and bobbin slow down quench propagation and quench-back. Different operating currents in each coil can also change the propagation rate along the magnet. In general, the adiabatic hot spot temperature in a coil is a function of the integral i^2dt. Coils with lower currents will have lower adiabatic hot-spot temperatures.

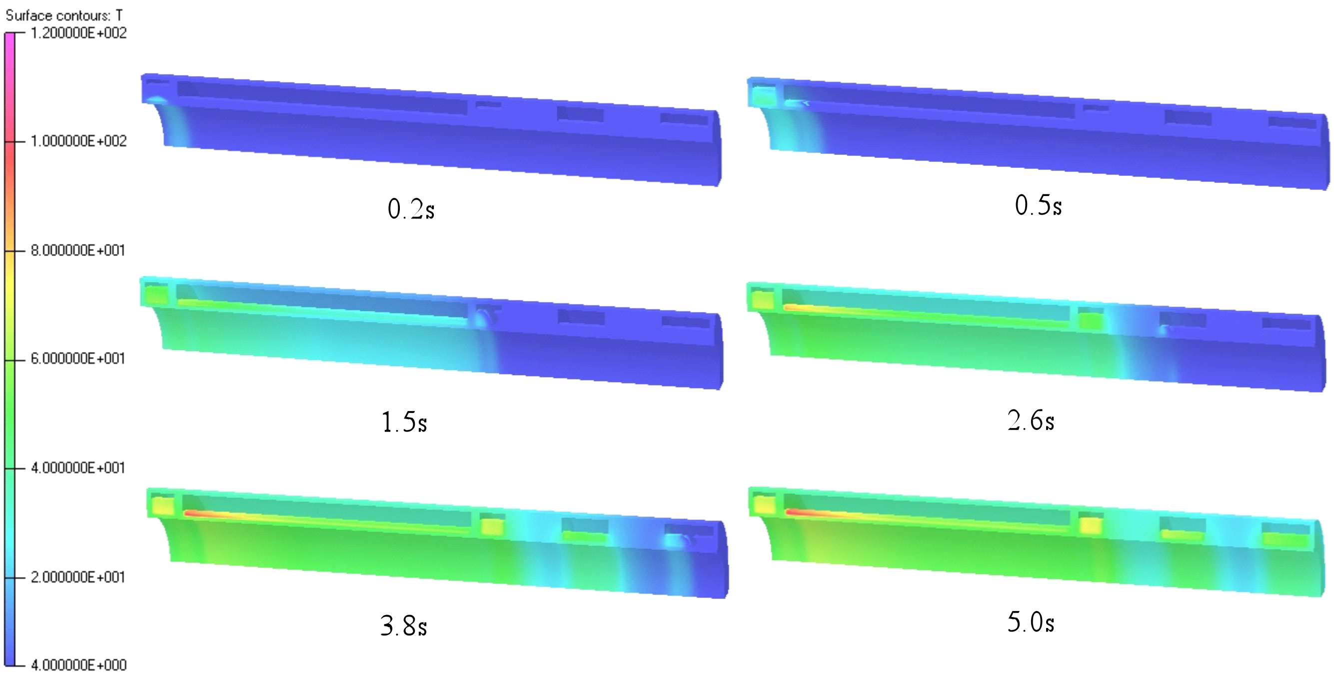

Fig. 7: Quench propagation along the magnet as a function of time after the quench started in coil E2 at 265 A. Quench back in the center coil is clearly seen.

D. *Quenches at lower currents*

A lower current reduces the coil stored-energy, but it also increases quench decay time constant in the coils. To verify this assertion, simulations were carried out at two lower currents. In these two cases, a quench was initiated at 200 A and 150 A.

The quench propagated from E2 to M1 in 6.2 s at quench current of 200 A, and in 8.3 s at the quench current of 150 A (see Fig. 8 and Fig. 9). At 200 A, the current decay time constant is ~5 s, and at 150 A, the decay time constant is ~7 s.

Low current quenches are safe for the coils, but things become complicated for the diodes and resistors. When a quench occurs in any coil, the power supply is disconnected. Currents will flow through the quench protection circuits for all coils even when other coils have not quenched. This means the current will flow longer in some diodes and resistors than others. Much of the helium cooling is lost early in a quench. There is conduction cooling to the cold mass. However, the diode and resistor integral of i^2dt is lower at the lower currents, so the adiabatic heating is less.

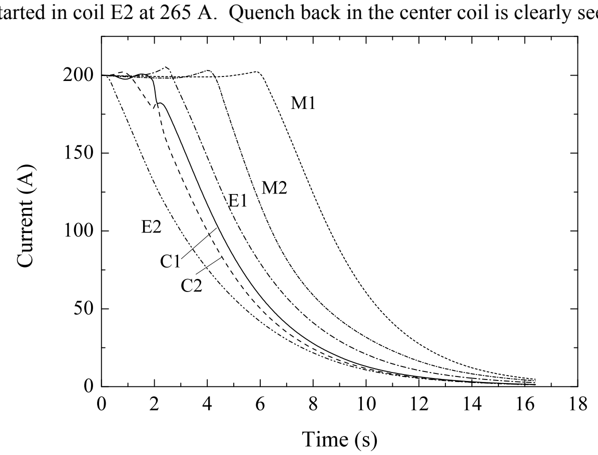

Figure 8: Current decay after the quench started in E2 at 200 A

The quench voltages were not calculated, because the total stored energy per coil is quite low. The worst-case voltage is <900 V to ground [10]. The actual voltages are much lower depending on the quench model used for the calculation [11].

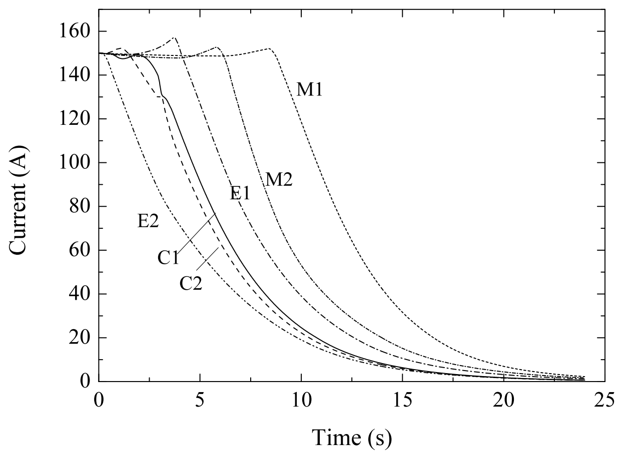

Figure 9: Current decay after the quench started in E2 at 150 A

III. Unbalanced Forces on the Thermal Shields

The unbalanced quench produces significant eddy currents in the mandrel, the helium vessel, the shield and the cryostat vacuum vessel. There can be a large lateral force on the mandrel and the shields [12].

Fig. 10 shows the lateral forces on four parts of an 1100-O aluminum shield as the quench propagated from one magnet end to the other at 265 A. The net shield lateral force can be as high as 160 kN without any slits in the shield.

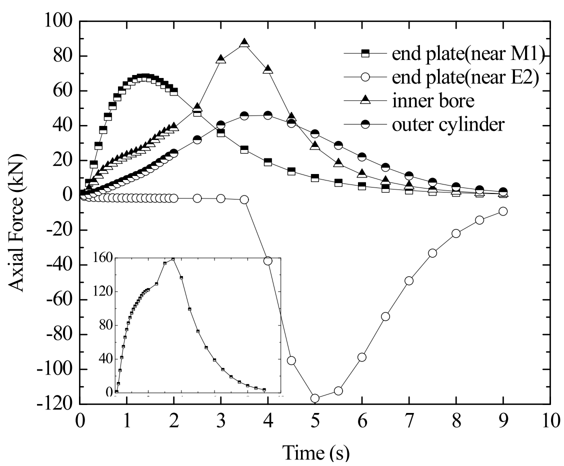

Fig. 10: Lateral forces on each part of 1100-O shield without slits. The overall lateral force on shields without slits is shown in small window.

This magnet shield is cooled using the first stage of five two-stage coolers. The magnet originally had a 6061-T6 Al shield without slits. The shield material had to be changed from 6061-T6 Al to 1100-O Al to reduce the peak shield temperature from 90 to <55 K. The resistivity of 1100-O Al is lower by an order of magnitude at 50 K. As a result, the shield needed to have slits to reduce the magnitude of the quench eddy currents and the magnetic forces.

Fig. 11 shows the reduced forces in each part of shields. The forces in each part have been reduced by 80 to 90 percent after the modification. It appears that the cuts reduced most of the forces in endplates and the outer cylinder. The resultant peak force in inner bore is around 6 kN, and the peak value of the overall lateral force is 19 kN.

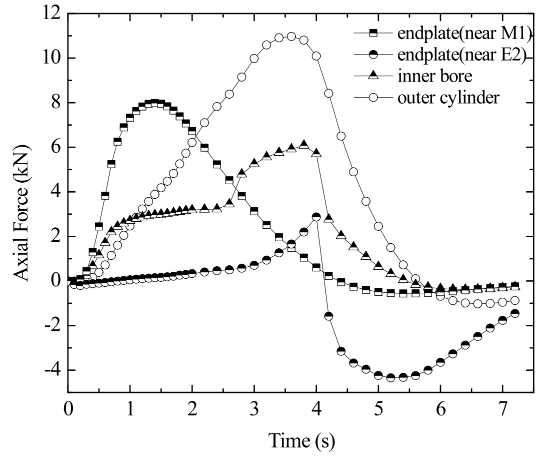

Fig. 11: Lateral forces on each part of the 1100 Al shield after slitting.

IV. Conclusion

The unbalanced quench was analyzed at different coil locations and different coil currents. The results show that the quench propagation along the magnet relies almost entirely on thermal diffusion. The quench of the center coil is speeded up by quench-back from the mandrel. A quench initiated at E2 end of the magnet is the worst case because of a longer quench propagation time. A low current quench has a longer decay time, but the hot spot temperature will be lower. A low current quench does not warm the diodes and resistors more than high current quench in this solenoid. The forces induced by eddy current in the shields for this solenoid have been analyzed. Changing the shield material from 6061-T6 Al to 1100-O Al introduced large eddy currents and lateral forces in the shield. Slitting the shield reduces the lateral forces significantly.

References

[1] P. Fabricatore, S. Farinon, U. Bravar, and M. A. Green, "The Mechanical and Thermal Design for the MICE Detector Solenoid Magnet System," *IEEE Transactions on Applied Superconductivity* 15, No. 2, pp 1255-1258 (2005).

[2] M. A. Green, C. Y Chen, T. Juang, et al, "Design Parameters for the MICE Tracker Solenoid," *IEEE Transactions on Applied Superconductivity* **17**, No. 2, pp 1247-1250, (2007).

[3] S. T. Wang, R. Wahrer, C. Taylor, et al, "The Design and Construction of the MICE Spectrometer Solenoids," *IEEE Transactions on Applied Superconductivity* **19**, No. 3, pp 1348-1351, (2009).

[4] S. Q. Yang, M. A. Green, G. Barr, et al, "The Mechanical and Thermal Design of the MICE Focusing Solenoid Magnet System," *IEEE Transactions on Applied Superconductivity* **15**, No. 2, pp 1259-1262, (2005).

[5] M. A. Green and H. Witte, "The Inductive Coupling of the Magnets in MICE and its Effect on Quench Protection," *IEEE Transactions on Applied Superconductivity* **16**. No. 2, pp 1304-1307, (2006)

[6] M. A. Green, H. Pan, and R. Preece, "Changes Made on a 2.7-m Long Superconducting Solenoid Magnet Cryogenic System that allowed the Magnet to be kept Cold using 4 K Pulse Tube Coolers," to be published in *Advances in Cryogenic Engineering* **59**, (2014).

[7] M. A. Green, "The Design of a Rapid Discharge Varistor System for the MICE Magnet Circuits," MICE Note-208, http://www.mice.iit.edu, (June 2008).

[8] X. L. Guo, M. A. Green, L. Wang, H. Pan, and H. Wu, "The Role of Quench-back in the Passive Quench Protection of Long Solenoids with Coil Sub-division," *IEEE Transactions on Applied Superconductivity* **20**, No. 3, p 2035, (2010).

[9] X. Guo, M. A. Green, L. Wang, H. Wu, and H. Pan, "The Role of Quench-back in the Passive Quench Protection of Uncoupled Solenoids

in Series with and without Coil Sub-division," *IEEE Transactions on Applied Superconductivity* **21**, No. 3, pp 2388-2391, (2011)
[10] M. A. Green, L. Wang, Z. L. Guo, et al, "Quench Protection for the MICE Cooling Channel Coupling Magnet using Quench-back and Sub-division," MICE Note 193, http://www.mice.iit.edu, (November 2007).
[11] H. Pan, M. A. Green, X. L. Guo, et al, "A Comparison of the Quench Analysis on an Impregnated Solenoid Magnet wound on an Aluminum Mandrel using Three Computer Codes," *IEEE Transactions on Applied Superconductivity* **23**, No 3, p 4901005 (2013).
[12] H. Pan, S. O. Prestemon, S. Virostek, et al, "Eddy-currents and the Force Analysis for the Thermal Shields of the MICE Spectrometer Solenoids," MICE Note 420, http://www.mice.iit.edu, (October 2012)

DISCLAIMER